TITLE: MAGNETISED TORQUE TRANSDUCER ELEMENTS

FIELD OF THE INVENTION

This invention relates to a torque or force sensor based on a magnetised transducer element, to a magnetised transducer element and to a method of forming such an element. The invention also relates to a shaft assembly including plural transducer elements and to a torque sensor system incorporating such a shaft assembly.

The invention will be particularly described in relation to transducer elements which are of magnetoelastic material and which are circumferentially magnetised, that is are of an annular form, e.g. circular form, which is magnetised in a closed loop around the annulus. The prior art transducer elements of this type provide a zero output at zero applied torque which can present a problem in practical applications as will be explained below. However, the invention has wider application to other magnetic-based transducer elements which need not necessarily utilise the phenomenon of magnetoelasticity in generating a torque-dependent or force-dependent measurement flux. Examples of this more general class of elements are what will be called herein "longitudinal magnetisation" and "radially-spaced magnetisation".

Longitudinal magnetisation provides an annulus of magnetisation, on a torque-transmitting shaft for example, in which the magnetisation extends in an axial direction at the surface over a defined length and acts to provide a closed loop of magnetic flux within the shaft. This may be visualised as a torus of magnetic flux. This torus of flux is distorted under torque to provide a torque-dependent tangential component of magnetic field, that is

a component normal to the radial direction.

Radially-spaced magnetisation is particularly applicable to disc-like parts subject to torque about the disc axis. The disc-like part is of relatively short axial

5   thickness and has two radially-spaced annular zones, e.g. circular in the most common form, which in the limit may be contiguous. The pair of spaced zones are each longitudinally magnetised in the axial direction or each circumferentially magnetised in a closed loop about the

10   axis. In each case a torque-dependent field is generated in a direction which is circumferential to the two zones, that is a field component that is tangential or normal to the radial direction. Transducer elements based on longitudinal magnetisation and radially-spaced

15   magnetisations also provide an output measuring field which is zero at zero applied torque.

Longitudinal magnetisation and radially-spaced magnetisations are described further below. As already indicated, the present invention will be described

20   particularly with reference to the known art of circumferential magnetisation transducer technology as applied to the measurement of torque.

BACKGROUND TO THE INVENTION

Transducers of the circumferentially magnetised type

25   are disclosed in related U.S. patents 5,351,555 and 5,465,627 (Garshelis, assigned to Magnetoelastic Devices, Inc.) and in U.S. patent 5,520,059 (Garshelis, assigned to Magnetoelastic Devices, Inc.). These patents describe torque sensing arrangements for a rotating shaft in which

30   a transducer ring or torus is secured to the shaft to

rotate therewith and to have the torque developed in the shaft transmitted into the transducer ring. The ring is of a magnetoelastic material circumferentially magnetised and the flux emanating from the ring due to the stress of

5   the ring under torque is detected by a non-contacting sensor system as a measure of the torque.

Another proposal is described in corresponding PCT application PCT/GB99/00736 filed 11th March, 1999, published under the number WO99/56099 on 4th November,

10   1999.

In this proposal a shaft of a material capable of exhibiting magnetoelastic material has a portion of it directly magnetised to support a circumferential magnetic field about the shaft axis, an approach which is contrary

15   to the thinking in the prior art. The magnetised portion of the shaft acts directly as the torque transducer element.

To illustrate the operation of a magnetoelastic torque transducer as represented by the above two proposals

20   reference may be made to Figs. 1A and 1B which show a separate ring transducer element secured to a shaft and a transducer element provided by a portion of the shaft itself. The shafts rotate about the longitudinal axis A-A.

In Fig. 1a the shaft 10, assumed to be of circular

25   cross-section, has the transducer ring 12 securely clamped on it by any of the means described in the three U.S. patents mentioned above. The transducer ring 12 supports a circumferential field M_c extending around the ring. If the shaft 10 is of low magnetic permeability, e.g.

30   paramagnetic, the ring 12 is mounted directly on the outer

surface of the shaft. If shaft 10 is ferromagnetic, that is of high permeability, a low permeability spacer (not shown) is mounted between the ring and the shaft.

In Fig. 1b, the solid circular shaft 10′ is of a magnetoelastic material having an integral portion 12′ of it directly circumferentially magnetised to provide the transducer element (the lines delineating portion 12′ are notional for clarity of illustration). As employed in previous torque sensors, with the shaft 10 or 10′ static and no torque applied, the circumferential field M_c is entirely contained within the transducer element 12 or 12′ so that an exterior non-contacting magnetic field sensor will not detect any field emanating from the transducer element. The application of a torque causes the contained field to skew and the opposite sides of the transducer to be oppositely magnetically polarised (i.e. N-S) to generate a torque-dependent magnetic flux that links the poles externally of the transducer element to enable a magnetic sensor to detect the torque-dependent external field M_e. It will be understood that this external field forms a torus or doughnut around the shaft. Many different types of magnetic field sensor devices are available and many sensor arrangement configurations of field sensitive devices may be employed. In the instance illustrated in Fig. 1b, the transducer element 12′ is preferably axially bounded by circumferentially-magnetised guard regions 14a and 14b, one to each side. These provide respective poles at the interface that are of opposite polarity, i.e. have a repulsive effect, to the poles of the transducer element

enhancing the emanation of externally detectable magnetic field from the transducer element for measurement of torque. The circumferential fields are induced to extend as deeply into the shaft 10' as possible.

5   Another proposal to enhance the emanation of magnetic flux from the transducer element is to provide the transducer element portion 12" shaft 10" with an integral annular section 16 of raised profile as shown in Fig. 1C, so that the upstanding sides assist in emanating magnetic

10   flux in an external loop. In contrast to the separate ring 12 of Fig. 1 in which all the field is confined in the ring, the annular section 16 is integral and homogeneous with the underlying shaft in Fig. 1c and the circumferential field extends into the body of the shaft.

15   This technique and that of using guard regions is discussed more fully in the aforementioned PCT publication WO99/56099. For the purpose of description of the principles underlying the present invention, no account will be taken of the guard regions where they are used.

20   Referring to Figs. 2a and 2b, when the transducer element - 12' is shown as an example, it is equally applicable to separate ring 12 - is subject to torque, a magnetic field M_e emanates from the transducer for sensing by a sensor arrangement 18 of any desired kind. The

25   external field has a magnitude proportional to the torque and a polarity dependent on the direction of torque T (CW or CCW) as indicated in Figs. 2a and 2B respectively.

The problem posed to some users of magnetoelastic torque transducer elements of the circumferential magnetic

field kind discussed above is that at zero torque in the shaft, the magnetic field output from the transducer element is zero. Outputs at or around the zero region are liable to be masked by noise. Another related problem

5   with circumferential magnetisation is calibrating the transfer function of a transducer, particular in checking the long term calibration where a stored magnetic field may change, usually (weaken) over the long term. A means of checking calibration without a lengthy procedure is a

10   desirable feature. The zero output at zero torque is also a problem with transducers employing longitudinal magnetisation and radially-spaced magnetisation. Longitudinal magnetisation has a detectable axial fringe field at zero torque upon which calibration can be based.

15   SUMMARY OF THE INVENTION

The present invention enables the provision of a real measurable output at zero torque with a range of linear measurement of magnetic field output against applied torque. The solution proposed by the present invention is

20   to induce the circumferential field in the transducer element when the element is subject to a torque, a concept that will be referred to as pre-torquing. This is in contrast to prior proposals in which the establishing of the circumferential field in the transducer element is done

25   without torque in the element. This pre-torquing of the transducer element during magnetisation may be also called processing torque.

One aspect of the invention is a transducer element as set forth in Claim 1 and another aspect is a method of

forming the transducer element as set forth in Claim 2.

Yet another aspect of the invention is a method of forming a transducer element in a portion of a shaft as set forth in Claim 11.

A further aspect of the invention is a shaft assembly having two axially-displaced transducer elements as set forth in Claim 14 and a still further aspect lies in a torque sensor system as set forth in each of Claims 18 to 21.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention and its practice will be further described with reference to Figs. 3 to 7 of the accompanying drawings in which:

Figs. 1a, 1b and 1c show examples of prior proposals for transducer elements magnetised to have a circumferential field,

Figs. 2a and 2b show an example of the emanated magnetic field for the transducer element of Fig. 1b subject to torques of opposite direction, i.e. clockwise (cw) and counter-clockwise (ccw);

Fig. 3 shows the circumferential magnetising of a transducer element under pre-torque and Fig. 3a shows the magnetising and pre-torque conditions as relating to a cross-section of the transducer element.

Fig. 4 shows a graph of magnetic field output (M_e) v. torque (T) for the circumferentially magnetised transducer element of Fig. 3 subject to a pre-torque.

Figs. 5a to 5d show response curves relating to different directions of pre-torquing and circumferential magnetisation;

Fig. 6 shows a sensor arrangement employing two transducer elements subjected to pre-torquing, Figs. 6a-6d graphically illustrating different responses obtainable with the two elements according to the direction of pre-torque and circumferential magnetisation respectively applied to the elements;

Fig. 7 illustrates one magnetising arrangement for obtaining circumferential magnetisation; and

Fig. 8 is a block diagram of a sensor and processing circuit providing automatic gain control.

Fig. 9 shows the creation of a zone of longitudinal magnetisation in a portion of a shaft;

Fig. 10a illustrates the toroidal form of magnetic flux in the longitudinal magnetised zone;

Fig. 10b illustrates the toroidal form of magnetic flux established by a two-step magnetisation process;

Figs. 11a and 11b illustrate the generation of a torque-dependent magnetic field vector component with a longitudinally magnetised transducer element in the absence of pre-torquing in accord with the invention, with the element under zero torque and under torque respectively and Fig. 11c is a magnetic vector diagram;

Figs. 12a and 12b show a torque-transmitting disc to which the invention is applicable, Fig. 12a showing a view of one face of the disc and Fig. 12b showing an axial section to which is added the magnetising arrangement for establishing radially-spaced annular zones of magnetisation and Fig. 12c is a magnetic vector diagram; and

Fig. 13 shows a view of one face of a modification of

the disc arrangement of Figs. 12a and 12b for circumferentially-magnetised annular zones.

DESCRIPTION OF PREFERRED CIRCUMFERENTIAL MAGNETISATION EMBODIMENT

5   Referring to Fig. 3, a solid shaft 20 of the kind shown in Fig. 1b is seen being subject to magnetisation M_c at a portion 22 while under a predetermined torque T_0. The magnetising method may use a permanent magnet 24 brought up adjacent to the portion 22 of shaft 20 while it is rotating 10   under the predetermined torque T_0. A preferred arrangement is shown in Fig. 7. Instead of a permanent magnet, an electromagnet may be used or the shaft subjected to an axially directed current. Various methods are available and some of these are disclosed in the above three U.S. 15   patents and particularly U.S. patent 5,520,059; and also in above-mentioned PCT publication WO99/56099. Alternatively the shaft may be held static with the predetermined torque T_0 applied to it while a magnet system is moved around it. Magnetisation by an axially directed current is also 20   applicable to the static case.

Fig. 3a indicates the directions of pre-torque T_0 and circumferential magnetisation M_c about the axis. The example shown has both of them clockwise. From Fig. 3a, it will be appreciated that their are four magnetising and 25   pre-torque conditions - T_0 is CW with M_c being CW or CCW; and T_0 is CCW with M being CW or CCW. These enable different torque response curves to be established as will now be described.

When the circumferential field M_c is induced in the

presence of torque T_o, this sets up the condition at which

zero external field is produced by the transducer element.

When the pre-torque is relaxed so that the shaft returns to

a zero torque state, the circumferential field is skewed to

5   a certain extent resulting in its opposite sides becoming

polarised as shown in Figs. 2a and 2b resulting in there

being is a quiescent external field M_o at zero torque.

Fig. 4 illustrates the magnetic field output M_e

available to an external sensor as a measure of torque T

10   for a given direction, say CW, of magnetisation. The

dashed line in Fig. 4 shows the conventional case without

any processing torque or pre-torque during magnetisation.

The torque axis of Fig. 4 shows the output field reversing

as the torque passes through zero, e.g. as the torque goes

15   from one direction (CW) to the other (CCW). At zero torque

in the conventional case the circumferential field is

trapped within the transducer element and there is no

external magnetic field available for sensing.

The full line A in Fig. 4 shows the effect of pre-

20   torquing as now proposed. The zero field output is at the

pre-torque value, i.e. at a know predetermined torque, here

shown as -To from a CCW pre-torque, providing a working

range of torque extending from a negative value to a

positive value in which the output field M_e is of the same

25   polarity so that there is no signal polarity reversal to

cope with in the processing circuitry, and with a real,

non-zero, field output M_0 at zero torque lying with a useful

range of torque response. It is to be noted that the

absolute axial direction of the external flux emanated for

a given direction of circumferential magnetisation differs for different materials.

Fig. 4 shows one of the possible four combinations of circumferential field direction and pre-torque direction mentioned above. Figs. 5a to 5d illustrates graphically the responses due to these four possibilities in a given shaft with clockwise and counter-clockwise directions being defined as in Fig. 3. Figs. 5a to 5d show a set of line curves of the four responses of detectable output field (M_e) v. torque (T) and which may be summarised according to the following table labelled a)-d) in conformity with Figs. 5a-d.

Pre-Torque (T_o) Direction	Magnetising Field Direction	Output Field (M) (Zero Torque)	Response Slope
a) CW	CW	$-M_o$	+ve
b) CW	CCW	$+M_o$	-ve
c) CCW	CW	$+M_o$	+ve
d) CCW	CCW	$-M_o$	-ve

It is to be understood that for different materials, the sign of M_o and the slope may be reversed. However, the outcome is still four responses of the kind shown. These may be combined for plural transducer elements as will now be described. It will also be appreciated that any response can effectively be inverted by the processing of the electrical signals obtained from the magnetic field sensor.

It will be appreciated that the requirements for measurement of torques in shafts depend on the

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circumstances in which the shaft is used. For example, it
may always rotate in a single direction or it may be
required to rotate bi-directionally. Torque sensors may
also be applied in circumstances where one end of the shaft
5   is fixed and the other end is subject to some applied
torque to be measured.

It is an important facet of the present proposals to
apply the pre-torquing concept to obtain advantageous
results from shafts having multiple axially displaced
10   transducer elements. Fig. 6 shows a shaft 30 having two
transducer elements 32 and 34 axially spaced along the
shaft but subject to the same torque in the shaft. It will
now be explained how an advantageous torque transducer
response can be achieved by using two transducer elements
15   with various combinations of pre-torque and circumferential
magnetisation directions. Each transducer element has its
output field sensed by a respective sensor arrangement 36
and 38 connected to processing circuitry 40.

One form of magnetic field sensor arrangement, using
20   saturable   inductor   sensing   elements,   and   signal
conditioning circuitry for generating the output indication
signal is that disclosed in published PCT application
PCT/GB98/01357, publication number WO98/52063.

Fig. 6a shows output responses, M v T, for the two
25   transducer elements 32, 34 being magnetised and pre-torqued
in accordance with conditions 5c) and 5b   - opposite
polarity circumferential fields of equal strength and equal
but opposite pre-torques. There will always be an output
from one transducer element even when the other is in the

zero output region. This avoids having to make use of a
single low output signal whose signal-to-noise ratio (SNR)
may be poor. Fig. 6b) shows output responses, M v T, for
the two transducer elements being circumferentially

5   magnetised with the same polarity and of equal strength but
with equal but opposite pre-torques - Figs 5b) and 5a).
These outputs may be combined (summed) at 40 to give a
resultant (dashed line) extending through the zero origin
but with the advantage that the measurements at or near

10   zero torque will have been made with signals of good SNR.

Figs. 6c and 6d are similar to the conditions of Figs.
6a and 6b but relate to cases where the circumferential
fields in transducers 32 and 34 are of different strengths.
Still more variations are readily visualized by using

15   different magnitudes of pre-torque. The transducer
elements whether they are of the kind integral with the
shaft or of the separately attachable ring type have
response characteristics established by any of the
parameters: direction of pre-torque and its magnitude, and

20   direction of circumferential magnetisation and its
strength.

Another important use of these multiple field
arrangements as the basis of an automatic gain control or
calibration for a torque sensor system. Take, for example,

25   the situation of Fig. 6a. It will be understood that if
the two output signals are summed, the sum should be a
constant value (M_s = 2Mo) at all torques. Over time the
circumferential fields may weaken so that if an initial sum
value M_i is stored as a calibration point, the later

obtained instantaneous sum M_s can be compared with M_c and used to derive a compensating value to correct later sensor measurements.

This compensation procedure can be applied where the two fields are not equal in strength but more computation will be required.

In order to better explain the application of automatic gain control or compensation, reference is made to Fig. 8 which shows a block diagram of a sensor and signal processing circuit for an arrangement broadly in accord with Fig. 6 to implement a measurement response of the kind illustrated in Fig. 6b using the inversion of one sensor signal to obtain a reference value such as indicated by M_s in Fig. 6a. The example to be illustrated has transducer regions 32 and 34 magnetised in accord with the responses of Figs. 5c and 5a respectively, namely, opposite but equal magnitude pre-torques and the same circumferential field direction, and of equal strength.

Referring to Fig. 8, it shows an analogue processing circuit 40 for processing the signals from sensors 36 and 38 of Fig. 6. The sensors 36 and 38 are illustrated as single coil sensors 60 and 62 respectively with which is included a respective driver and control circuit and respective buffer amplifiers 64 and 66. The manner in which coil-type magnetic field sensors are employed in transducer systems and a specific circuit for this purpose are disclosed in PCT application GB98/01357 published under the number WO98/52063. Each of the buffer amplifiers 64 and 66 has associated with it a means for adjusting the

amplifier gain, assumed to be nominally unity, and the amplifier offset. The sensors 60 and 62 have respective voltages V_1 and V_2 induced in them. The sensors are mounted to have the voltages V_1 and V_2 induced in the same sense and

5   to have any signal due to the earth's magnetic field or other extraneous field induced in the same sense. Thus each of V_1 and V_2 is in practice the resultant of the torque dependent magnetic flux sensed thereby and any extraneous unwanted flux.

10   In one of the sensors, 38, the input signal is inverted so that the buffer amplifiers produce output signals V_1 and $-V_2$ for further processing. The response curves at this point are now equivalent to Fig. 6a. The circuit 40 comprises a main signal path 70 and an automatic

15   gain control loop 80. The circuit is designed to combine the signals V_1 and V_2 to provide an output voltage V_o following the torque-dependent dash line curve in Fig. 6b, i.e. $V_o = V_1 - V_2$ in the ideal case. It will be noted from Fig. 6b that V_1 and V_2 are of equal magnitude, follow torque

20   curves of equal slope, one increasing linearly with torque T from the zero torque point and the other decreasing linearly with torque T from that point.

In the main signal path 70, the voltages V_1 and $-V_2$ are applied to inputs of respective summing amplifiers 72 and

25   74 of equal (unity) gain. Each amplifier has a second input receiving a signal whose derivation is described below. The output of amplifiers 72 and 74 are applied as inputs to an output summing amplifier 76 to provide the output V_o. Amplifier 76 is a gain controlled amplifier

having an input 78 for receiving a gain control signal from the gain control path 80.

The automatic gain control (AGC) loop includes a difference amplifier 82 to which the voltages V_1 and $-V_2$ are applied to thereby obtain a reference signal which is a sum signal $(V_1 + V_2)$ providing, in the ideal case, a constant value signal across the torque range equivalent to M_s in Fig. 6a. This sum signal is applied through block 84 to develop a signal at appropriate level to control the gain of summing amplifier 76 in accord with an initialising procedure discussed further below. The action of this forward gain control loop is further described below.

The output of difference amplifier is divided-by-2 at 86 and the output is passed directly to a second input of amplifier 72 and via an inverter 88 to a second input of amplifier 74 to re-enter the main signal path.

The operation of the circuit 40 is as follows.

The signals applied to the two inputs of amplifier 72 are V1 and a signal derived from the summation of V_1 and V_2 in the AGC loop 80. The signals applied to the two inputs of amplifier 74 are $-V_2$ and the same second signal as applied to amplifier 72, but inverted. The signals applied to the inputs of amplifier 76 from amplifiers 72 and 74 are summed subject to a gain control to provide an output

$$V_o = k \ (V_1 - V_2).$$

It is worth noting here that the sensor devices 60 and 62 were so arranged that any induced signal components, such as from the earth's magnetic field were in the same

sense with respect to V_1 and V_2 so that these components will be cancelled from the final output.

The sensor circuits 36, 38 and the processing circuit 40 are initially set up so that the output V_o represents the

5   desired dashed line response of Fig. 6b by combining the V_1 and V_2 responses as a function of torque, e.g. the responses 32 and 34 of Fig. 6b.

It will be understood that the compensation techniques discussed above could be implemented in software. For

10   example, the sensor output signals V_1 and V_2 may be digitised and the functions of the signal processing circuit 40 implemented on the digitised signals using software routines.

One of the potential problems with circumferential

15   magnetic fields, such as 32 and 34, is that they may weaken over time. Thus for the same torque values, lesser values of V_1 and V_2 will be obtained. The initialising procedure may make use of the magnetisation established under the pre-torque values (Fig. 6b). The sum of V_1 and V_2 at the

20   sensor buffer output can be identified with a specific torque value - $2T_o$-in this example and thus with a torque measurement sensitivity (volts/Nm). The offset and gain (slope) resistors R1 and R2 associated with the sensor buffer amplifiers provide a means of ensuring that the sum

25   $(V_1 + V_2)$ to be used as a reference is constant across the range of torque measurement. Later changes in the summation $(V_1 + V_2)$, such as weakening of the transducer region fields, is then compensated by adjusting the gain of amplifier 76 (i.e. the factor "k") by means of the AGC loop

80.   This sets the gain or scaling factor of the amplifier

76.   The loop can also act to compensate perturbations in

the V_1 and V_2 signals during, for example, rotation of a

shaft whose torque is being measured.   This compensation

5   can be afforded on a real-time basis as the shaft is

rotating.

        The system can compensate for the effect of

temperature changes on the basic sensor sensitivity.   It

can compensate for changes in the distance between the

10   magnetic field sensor and the shaft as the shaft rotates.

Generally, aging effects, e.g. leaching away of the

transducer region fields will be compensated to maintain

the initial torque sensitivity.

        Reverting to the magnetising arrangement indicated at

15   24 in Fig. 3, a more preferred arrangement is seen in Fig.

7 which shows a cross-section through the portion 22 to be

magnetised.   A pair 50 of opposite polarity magnets have

respective ends 52, 54 adjacent the shaft but a little

spaced to generate a field between them having an

20   essentially circumferential direction and through which the

circumference of the shaft is rotated.

        The practice of the invention has so far been

described with reference to circumferential magnetisation.

Embodiments will now be described which utilise the above-

25   mentioned longitudinal and radially spaced magnetisation,

assuming transducer elements of ferromagnetic material.

LONGITUDINAL MAGNETISATION EMBODIMENTS

        The nature of longitudinal magnetisation has been

outlined above.   The techniques taught above for a

circumferentially magnetised transducer element are also applicable to a longitudinally magnetised transducer element or a pair of such elements.

Fig. 9 shows how an annulus of longitudinal magnetisation is applied to an integral portion of a shaft. The portion is to provide a transducer element and it at least is of magnetic material. In Fig. 9 a shaft 110 of magnetic material is rotated about its axis so that a portion 152 of it is magnetised by the axially-spaced north-south poles NS of a magnet arrangement 150. This may be conveniently an electromagnetic which enables the magnetisation to be readily controlled. The magnet system may be moved about the shaft. The result of this magnetisation is to produce an annular zone of surface magnetisation 154 as shown in Fig. 10a having NS poles as indicated. It extends as an annulus about the shaft axis having the remanent magnetisation of the same polarity around the axis of the shaft and axially-directed. As indicated, the annular magnetisation tends to form a closed flux path within the shaft interior to annulus 154 so that a toroid of magnetic flux is established about the shaft axis. What is important is the magnetic field detectable exteriorly of the shaft as will be shortly explained.

The toroidal flux concept can be enhanced as is shown in Fig. 10b which shows a surface adjacent annular magnetised zone 154 within which an interior annular magnetised zone 156 of opposite polarity is established. The two zones combine as shown to provide the torus of closed loop magnetic flux. The magnetisation is obtained

by a two-step procedure. Firstly a deep annular region of
the polarity of zone 156 is formed by the magnet 150. Then
the surface adjacent zone 154 is formed by reversing the
magnetisation polarity of surface adjacent region of the

5   deep region.

Turning to the practical utilisation of the resultant
transducer element, reference is made to Fig. 11a which
shows the magnetic field of zone 154 as seen at the surface
of the shaft in the absence of torque. The arrow Mf

10   indicates a fringing field which will extend generally in
the axial direction between the poles of region 154 in the
ambient medium usually air.

Fig. 11b shows the effect of putting the shaft, and
thus transducer element portion 152, under torque in one

15   direction about the axis of shaft 110. The longitudinal
field in zone 154 is skewed as shown by the arrows (the
skew is exaggerated for clarity of illustration). The
external fringing field is likewise skewed or deflected as
represented by magnetic vector Mf' (Fig. 11c). Also

20   generated is a vector component Ms which in this embodiment
extends circumferentially about the circumference of shaft
110. The component Ms is tangential to the shaft at any
point, that is perpendicular to the local radius. It is
the Ms component that provides the component for measuring

25   torque by means of an appropriate oriented magnetic field
sensor or group of sensors. Ms is a function of torque.
If the torque is in the opposite direction the direction of
Ms is reversed. At zero torque, Ms has a zero value. This
results in the same problem as already described for

circumferential magnetisation, namely the difficulty of measurement at zero or near zero torque.

The solution adopted is the same as for circumferential magnetisation, namely that of pre-torquing the shaft portion 152 while establishing the magnetisation of it so that on allowing the shaft to relax to zero torque, the quiescent field is skewed with a detectable Ms component. This technique can be extended to more than two longitudinally magnetised regions as taught above in respect of circumferentially magnetised regions.

RADIALLY-SPACED MAGNETISATION

The principles given above can be applied to radially-spaced magnetisations which find particular, though not exclusive, application in torque transmitting discs.

Figs. 12a and 12b show a face view and an axial section of a disc 210 which is mounted on a shaft 220 for rotation about its axis A-A and carries, for example, a gearing 224 at its outer periphery for enabling transmission of torque through the disc. Also shown is the provision of a magnet system comprising magnets 216 and 218 on opposite sides of the disc to establish two magnetised zones 212 and 214. Each zone is established as an annulus about the axis A-A, as by rotating the disc between the magnets. Each zone is longitudinally magnetised in that the magnetisation extends in the axial direction and the two zones 212 and 214 have opposite polarities of magnetisation. The two magnetised zones provide a transducer element 222 (the magnets 216, 218 being removed) which from face 211, say, appears as in the

segment of the disc shown in Fig. 12a. At the surface 211
zone 212 provides an annular pole (N) of one polarity and
zone 214 an annular pole (S) of the opposite polarity
between which an exterior magnetic flux Mr (Fig. 12c) is
5   established to link the poles.   The exterior magnetic
field vector is radial at any point around the annuli.
Under torque the vector is deflected or skewed from the
radial to a position Mr' to provide a circumferential or
tangential component Ms which extends around the annulus.
10   Ms is a function of torque having a zero value at zero
torque unless the teachings of the present invention are
adopted. Thus as in the earlier described embodiments, the
magnetised zones 212 and 214 are established while torque
is applied (pre-torquing) so that a detectable value of Ms
15   is generated when the disc is relaxed to a zero torque
state.

Fig. 12a also shows sensors 228a-228d for detecting
the circumferential component M_s and sensor 226a-226b for
detecting the radial component Mr used as a reference.

20   Fig. 13 illustrates how the disc-like torque
transducer assembly can be adapted to work with
circumferential magnetisation. Fig. 13 is a face view of
a disc 350 through which torque is transmitted between a
drive applied on the axis A and the periphery or vice versa
25   as previously described.   In this embodiment, there is a
transducer region 352 which comprises an inner annular
region 354 and an outer annular region 356. The regions
354 and 356 have opposite polarities of magnetisation as
indicated by the respective arrows.   The circumferential

magnetisation may be applied through the face 358 using a magnet arrangement of the kind shown in Fig. 7.

In the absence of torque the circumferential fields in regions 354 and 356 will be trapped within the annular
5   regions. However, under torque the fields become skewed in the manner well-known with prior art circumferential transducers, e.g. Garshelis U.S. patents 5,351,555, 5,520,059 and 5,465,627. The consequence is that at face 358 the regions 354 and 356 develop magnetic poles of
10   opposite polarity. The polarity is dependent on the direction of torque.

A radial measurement field Ms is generated externally of the surface 358 between regions 354 and 356, the radial magnetic flux being a function of torque. The radial flux
15   can be sensed by sensors disposed as for the radial (reference) flux in Fig. 12a, e.g. sensors 226a-d. In contrast to Fig. 12a it is seen that the detectable torque-dependent flux is radial, rather than circumferential, but there is no reference field component available.

20   The above modification also suffers from having a zero field Ms at zero torque unless the circumferential fields are established in regions 354 and 356 by pre-torquing the disc while establishing the fields in accord with the teaching given above.